Successful Borehole Seismic Imaging of Injected CO_2 in a Deep Saline Formation

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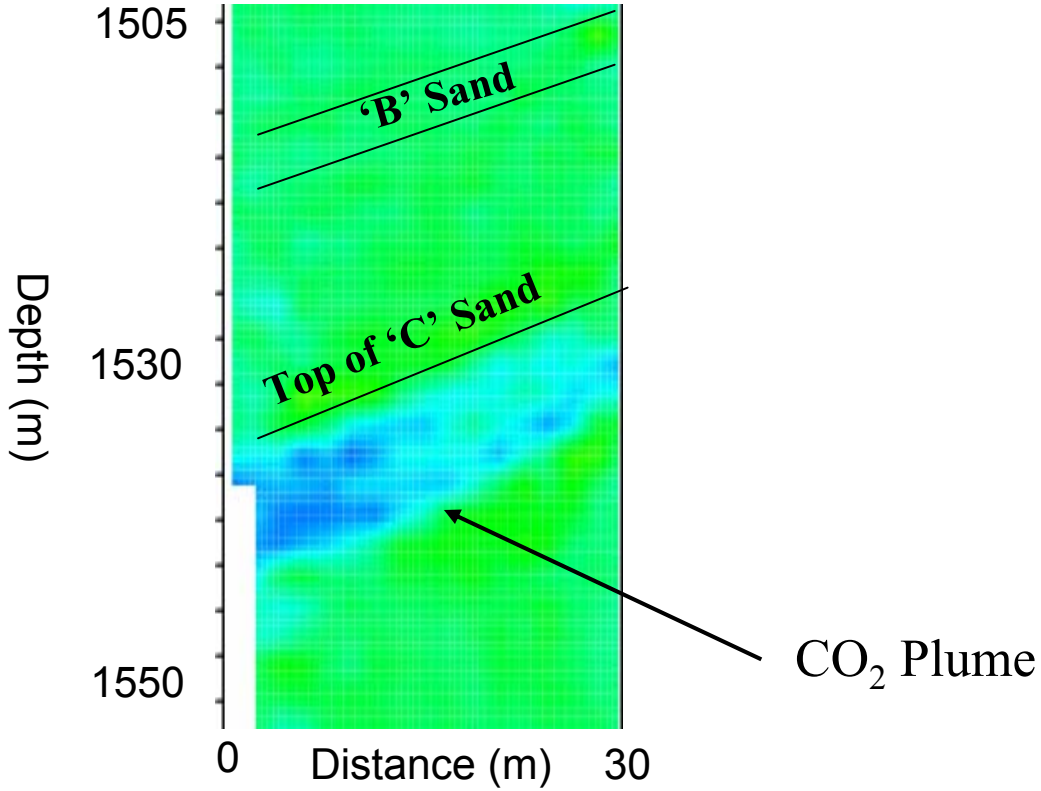


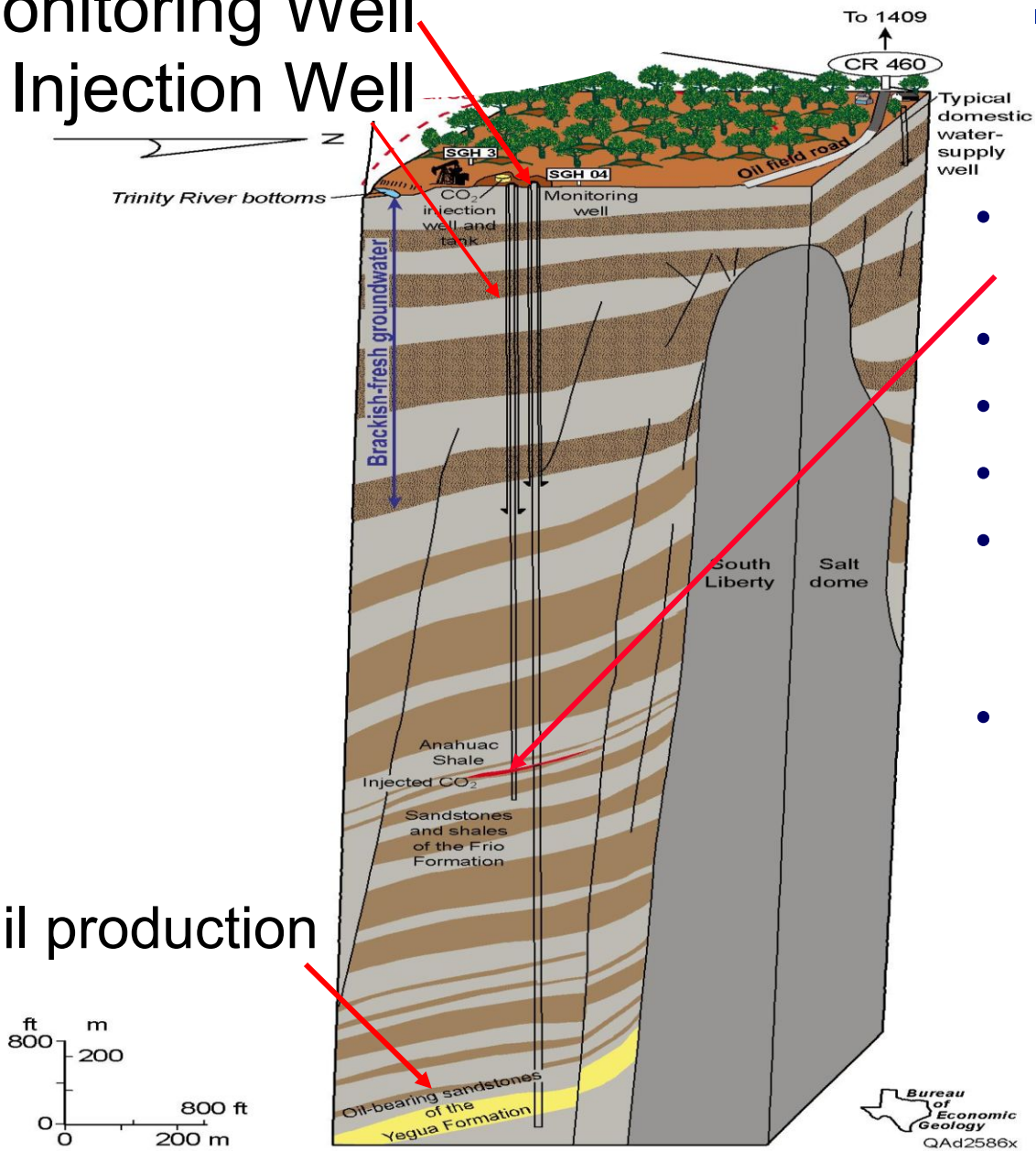
Outline

- Background of the CO_2 Sequestration Pilot
- Goals of Crosswell and Vertical Seismic Profile (VSP)
- Data Acquisition
- VSP Estimate of Plume Extent Compared to Flow Model
- Crosswell Tomography and CO_2 Saturation Estimate
- Integration of Crosswell and VSP using Seismic Modeling
- Conclusions
- Plans for Frio-II

Frio Brine Pilot, Dayton, Tx

Monitoring Well

Injection Well



Oil production

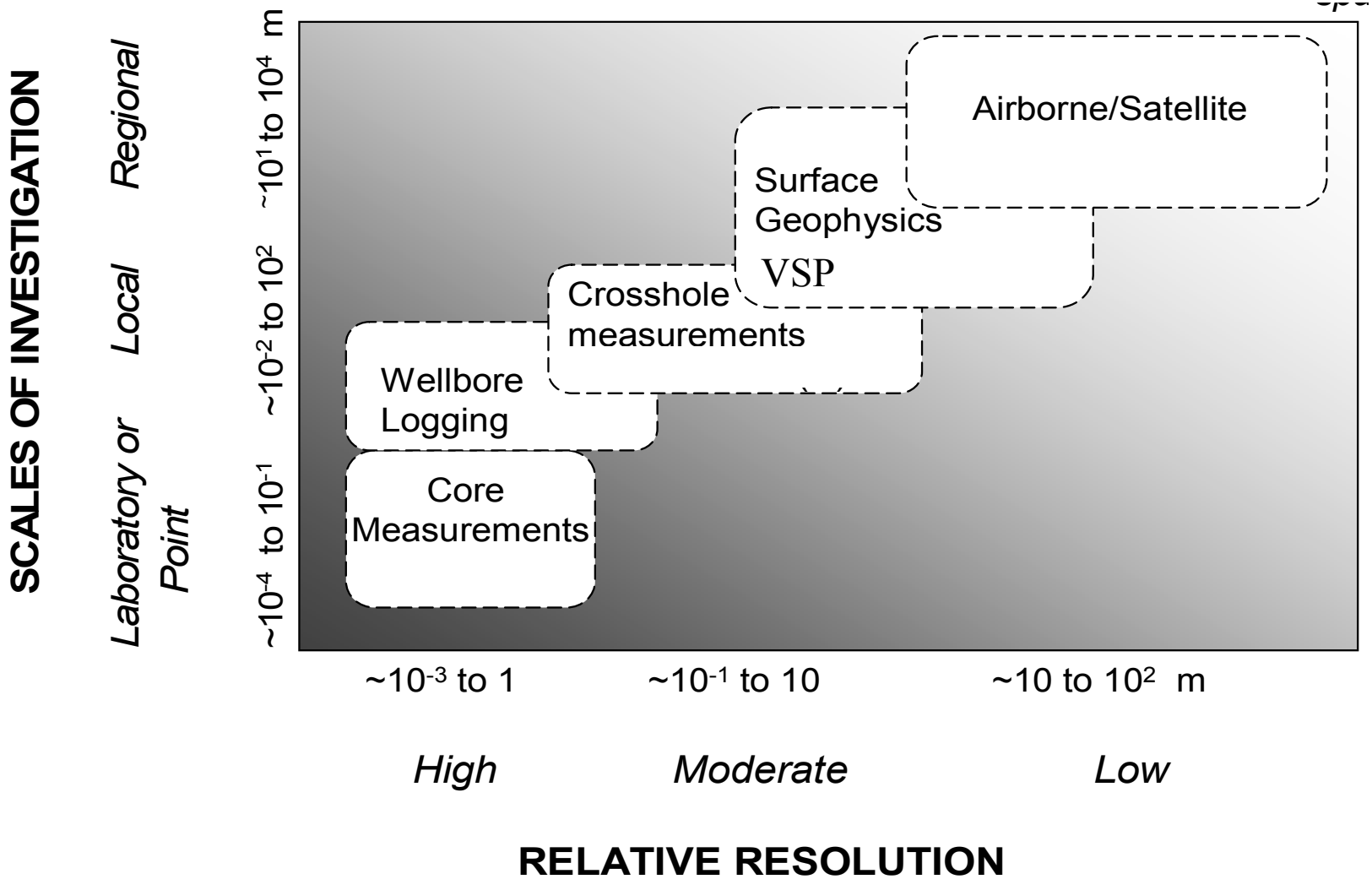
- Injection interval ~7 m thick at 1530 m depth
- ~1600 metric tons CO_2
- Well spacing ~30 m
- Dip ~20 deg.
- Frio 'C' Sandstone: porosity 30%, permeability 1.5 Darcys, brine filled
- 150 bar, 53 deg. C, supercritical CO_2

Frio Site 2004

Work over rig at injection well, crane at monitoring well

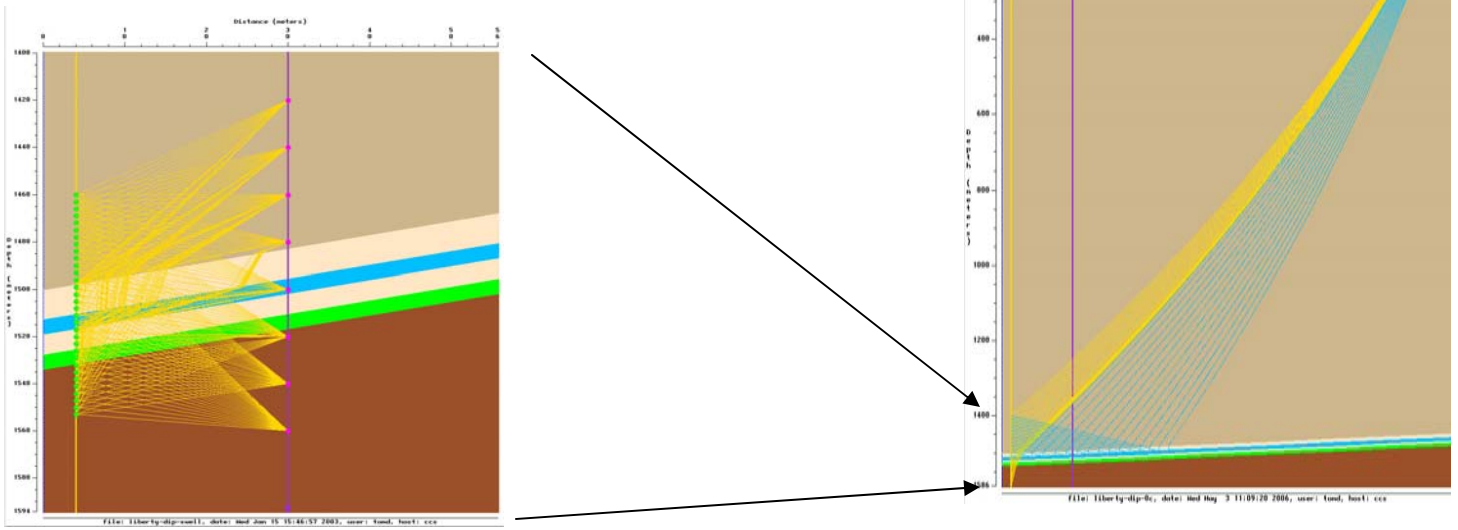
Recording truck, sensor string on reel, wireline truck

Goals of Seismic Monitoring: Scale/Resolution of Geophysical Data



Goals of Seismic Monitoring: Time-Lapse Surveys (Pre and Post Injection)

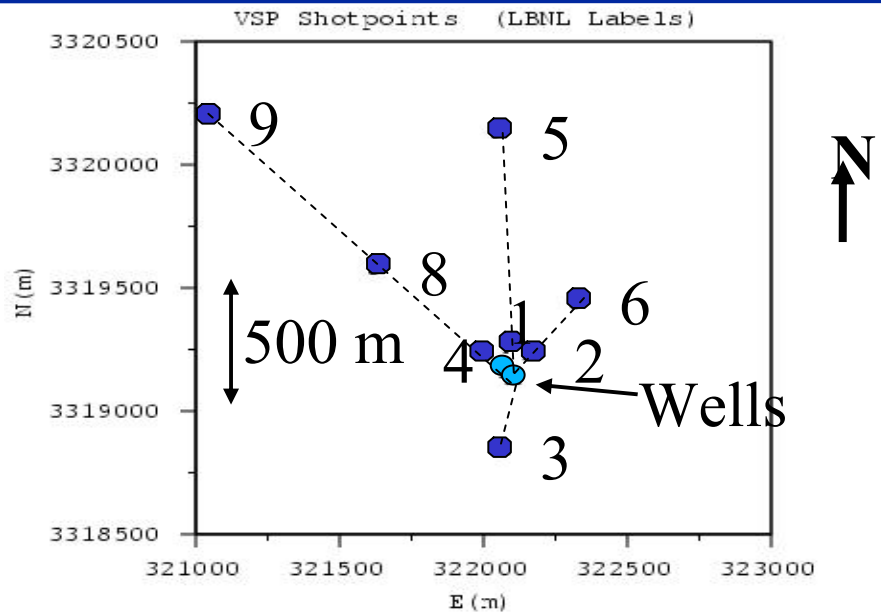
- Crosswell
  - Spatial mapping of CO_2 between wells
  - Combine with other measurements to estimate CO_2 saturation between wells.
- VSP
  - Spatial mapping of CO_2 beyond the well pair
  - Imaging of nearby structure (faults, etc)



Data Acquisition

- Orbital vibrator source for crosswell; explosive source for VSP
- P/GSI 80 level 3-component sensor string for crosswell and VSP
- Crosswell 1.5 m spacing, VSP 4 m spacing
- Pre Injection Survey: July, 2004
- Post Injection Survey: Nov. 28, 2004 (1.5 months after injection)
- Both wells' perforations were cemented during both surveys

VSP: 8 Source Points
80 Sensor levels at ~8m spacing



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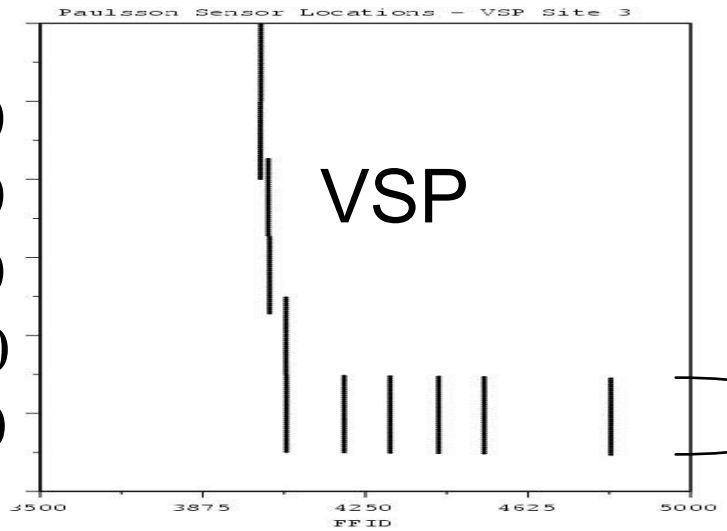
Source Points – Plan View



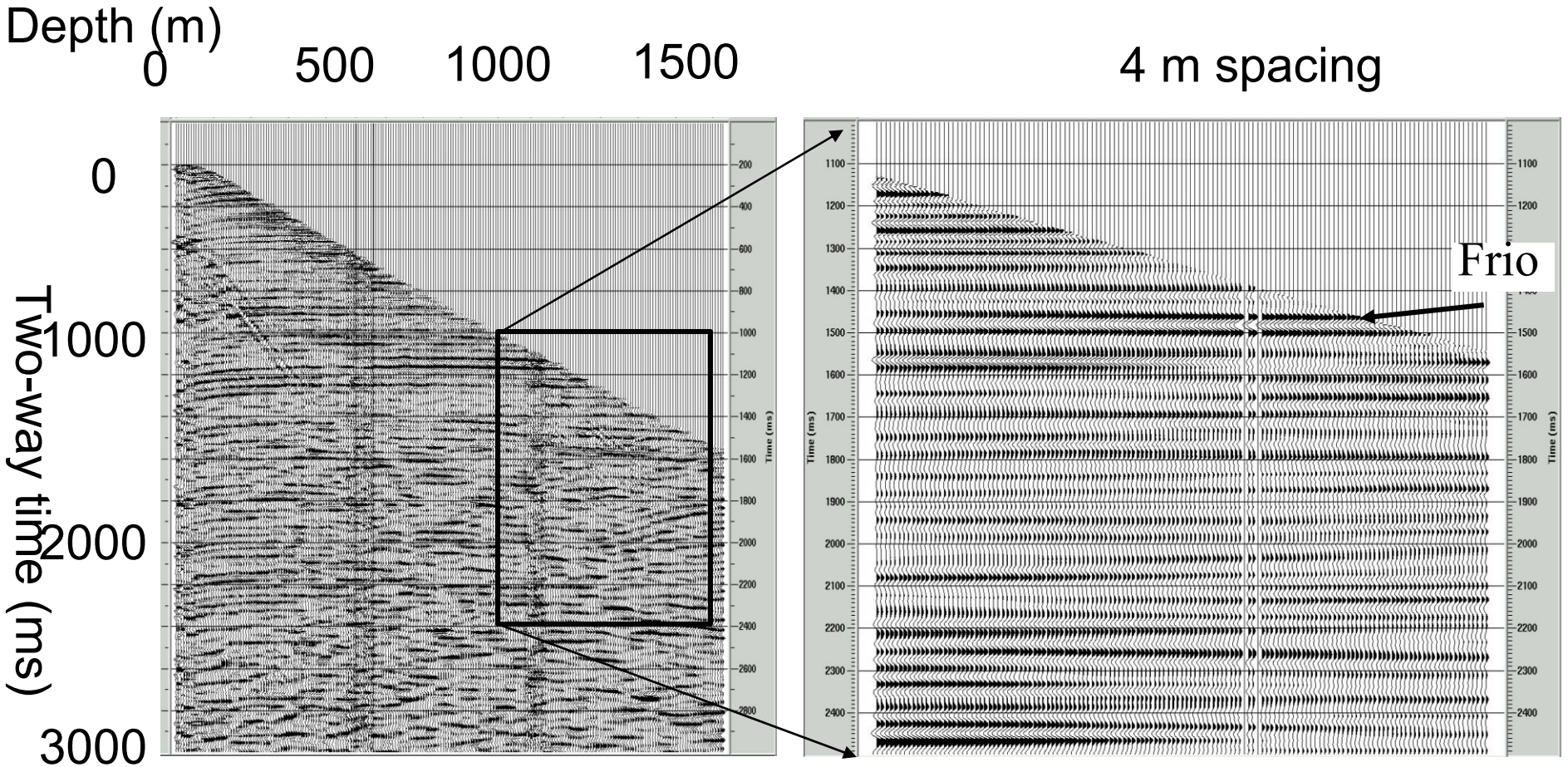
Sensor Depths

Crosswell Fans

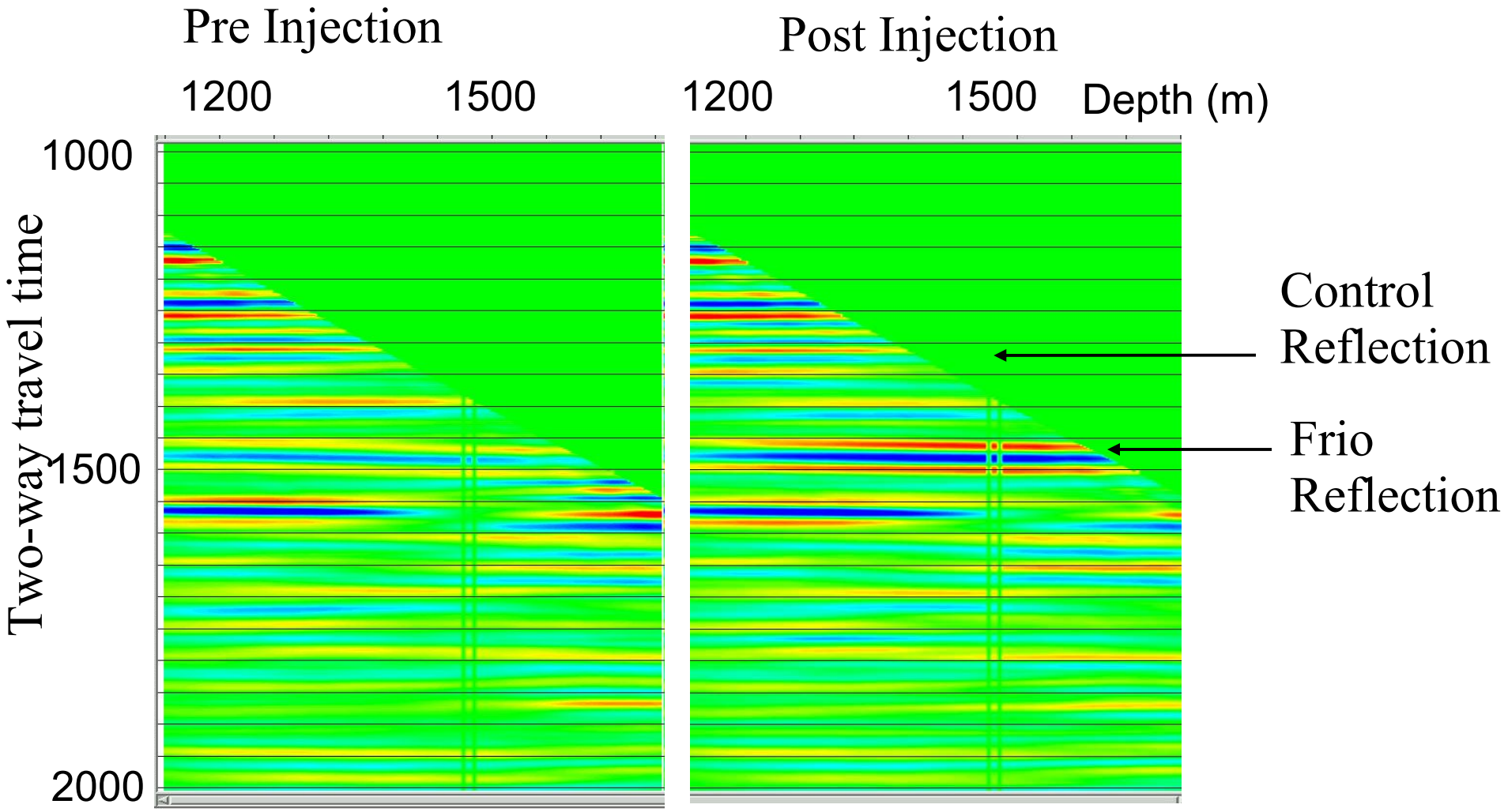
VSP Reflection Section Site 1

Entire VSP
Reflection Section

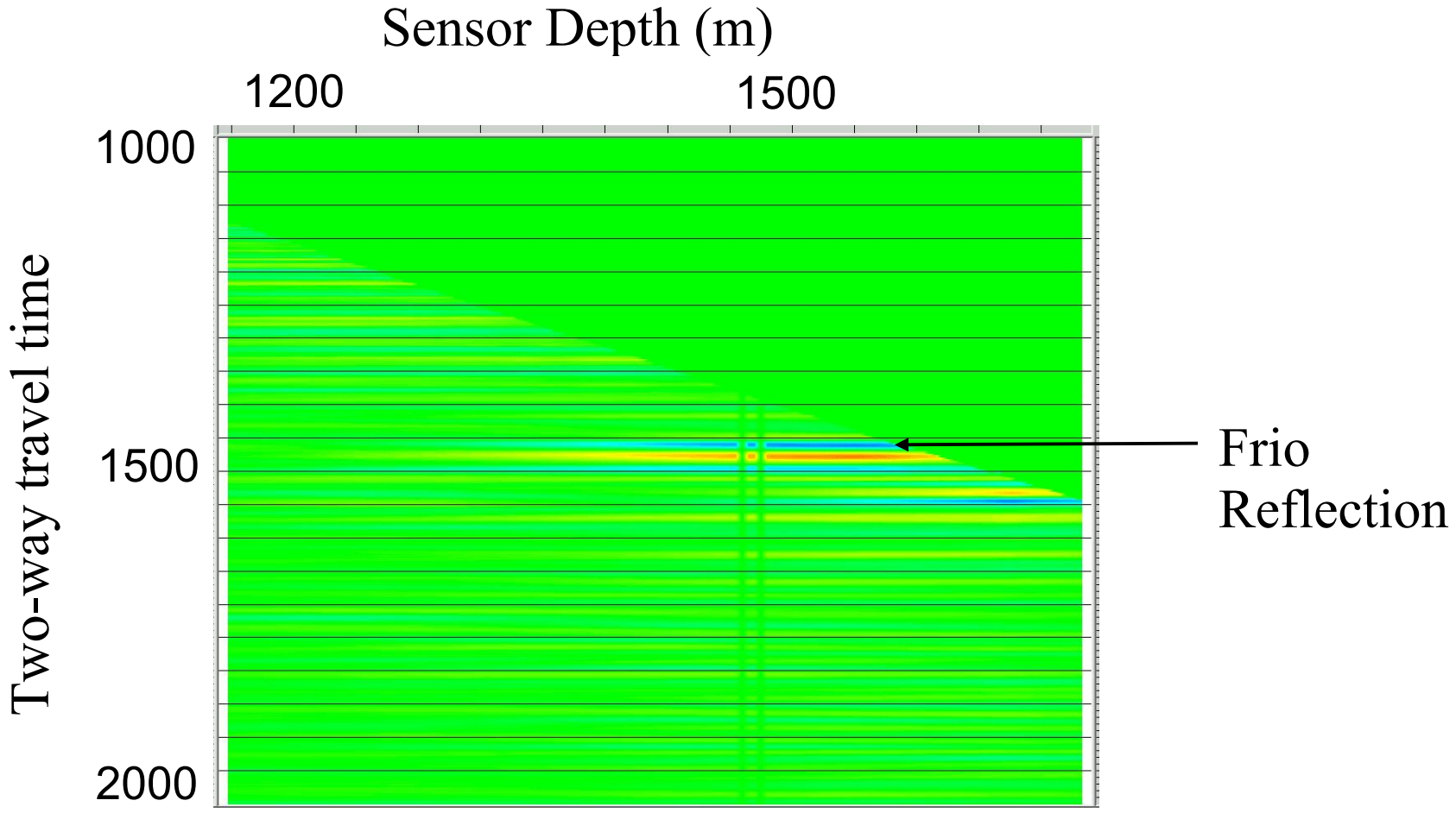
Frio Analysis Window
Enhanced Reflection



VSP Time-Lapse Reflection Amplitude Change
Site 1

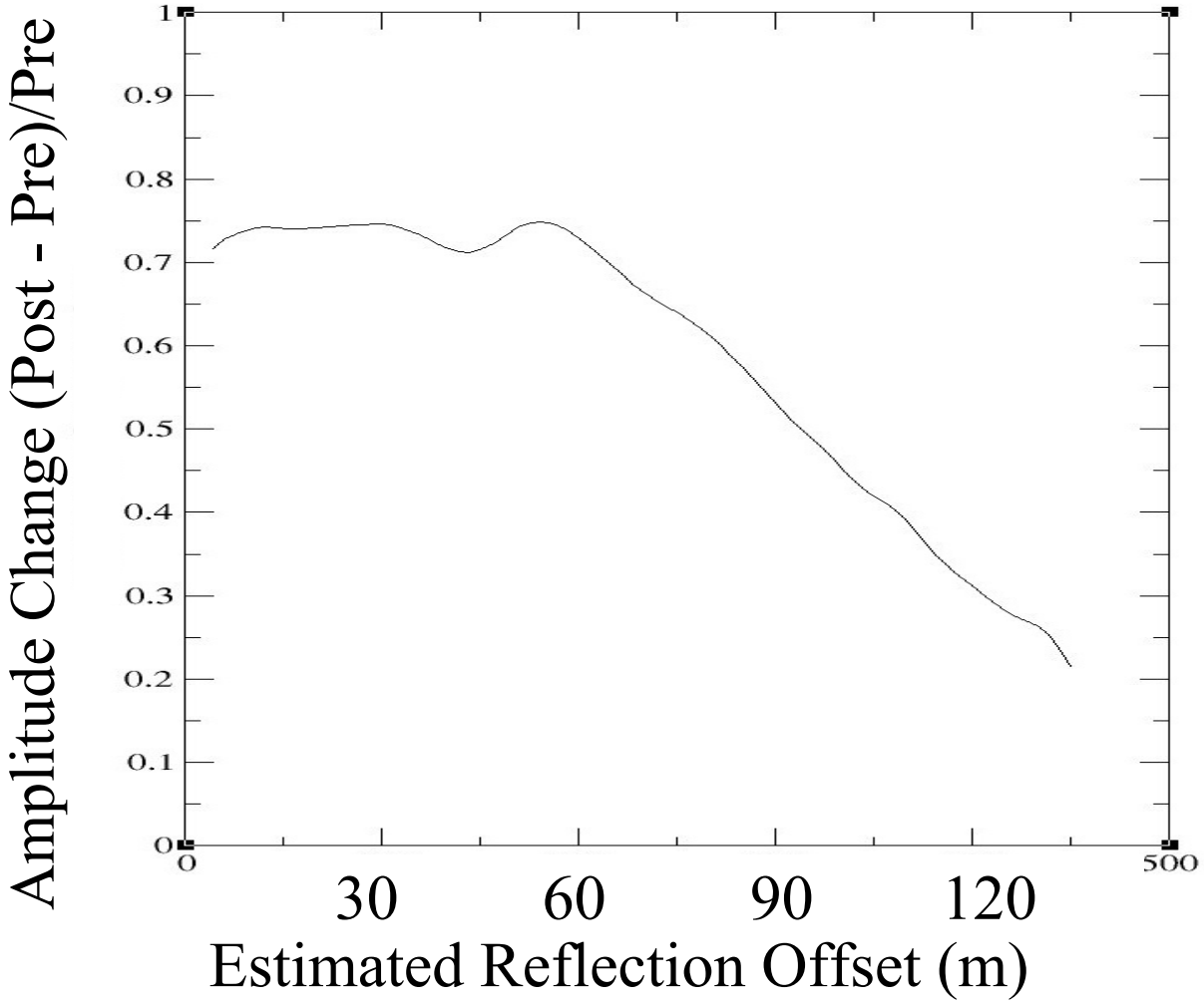


Site 1 Reflection Difference (Post – Pre)



Major change in Frio due to CO_2 injection.
Smaller change below Frio probably due to transmission through Frio.

Site 1 (North): Estimated Plume Extent

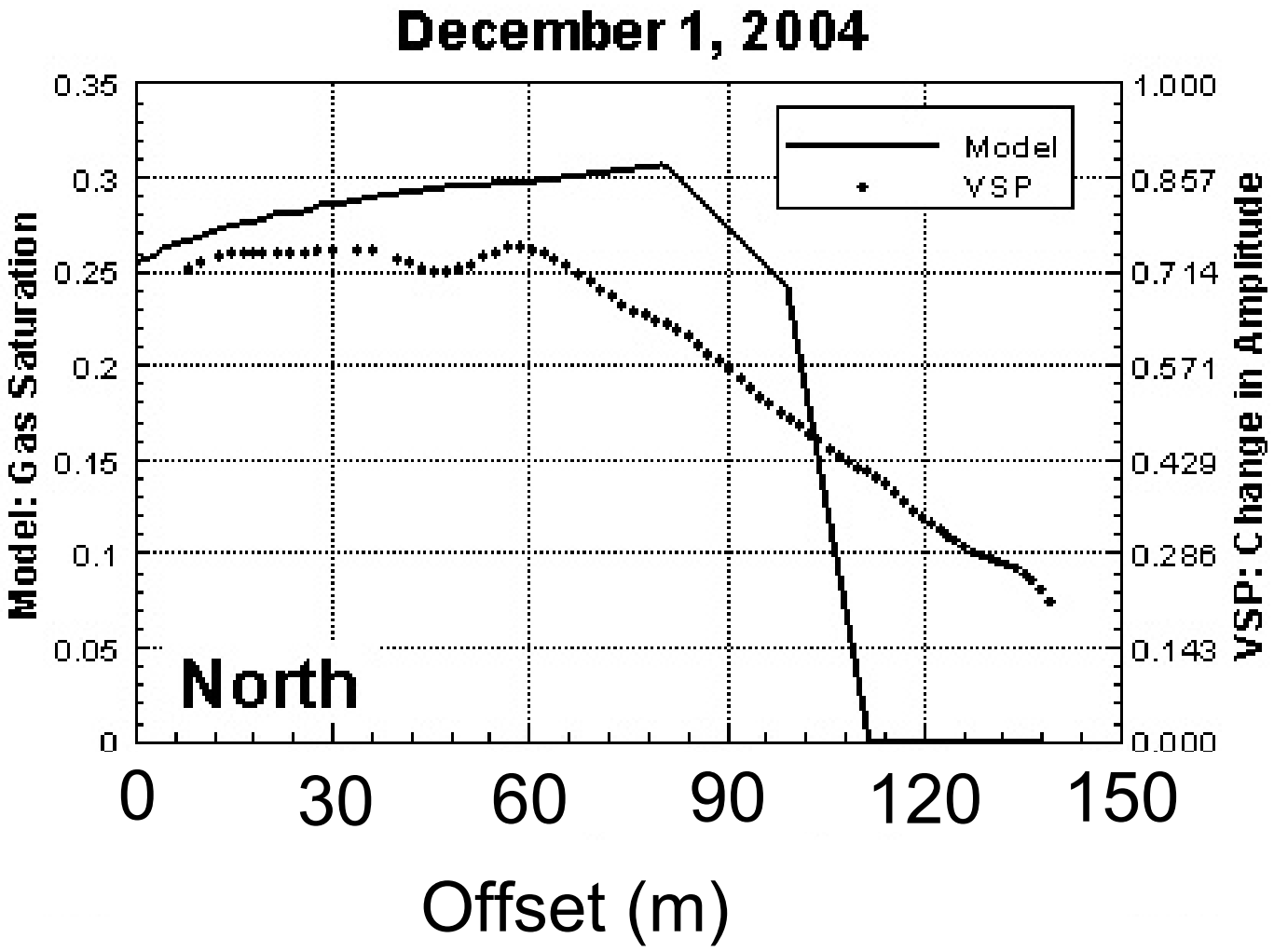


Over 70% increase in peak reflection amplitude. This is a strong response.

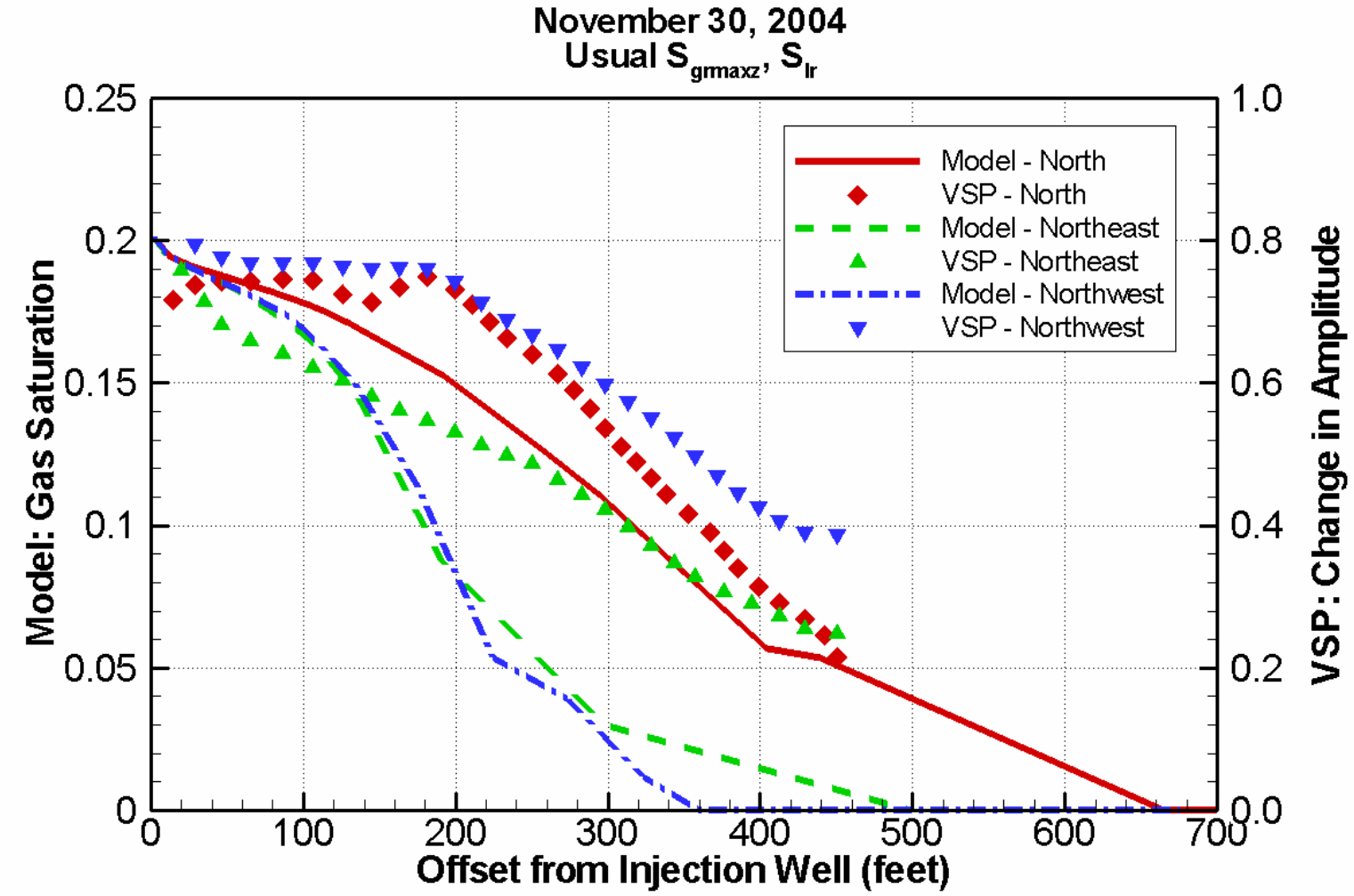
Amplitude change is a function of CO_2 Saturation.

Result:
VSP can be used to Estimate the extent of CO_2 plume.

Comparison of VSP and Modeled CO_2 Saturation

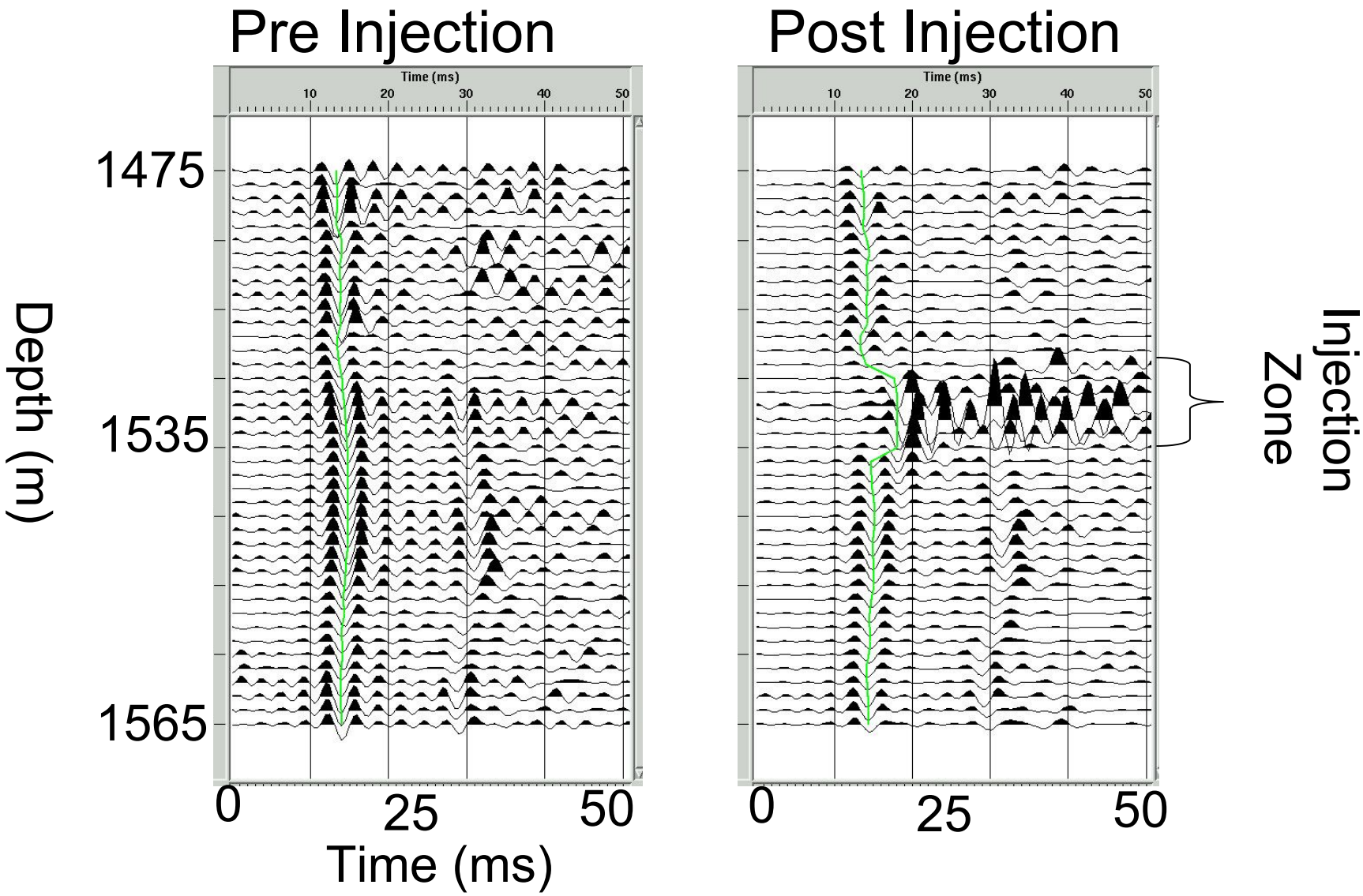


Comparison of 3 Azimuths



Flow modeling: C. Doughty

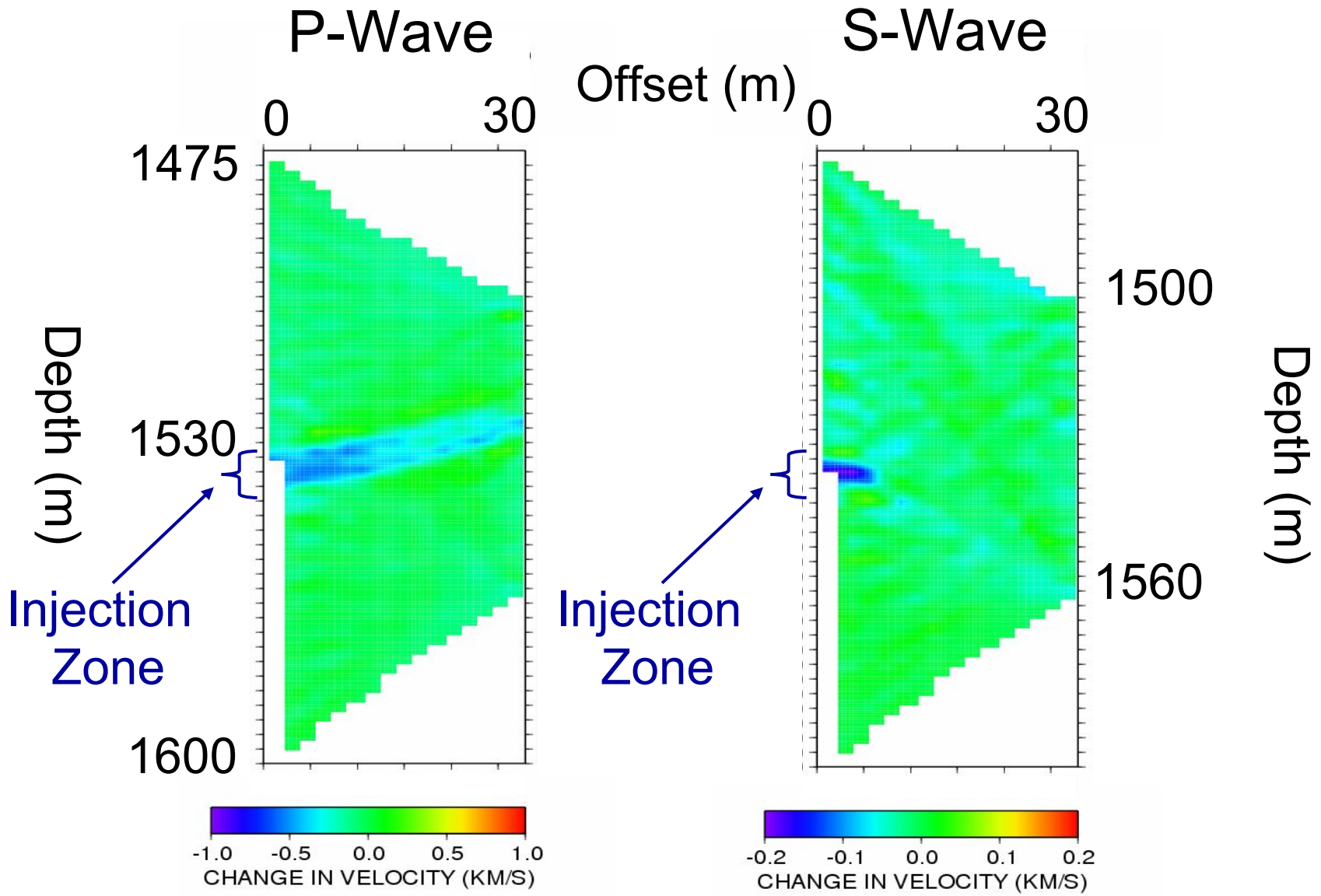
Crosswell : Raw seismograms show change



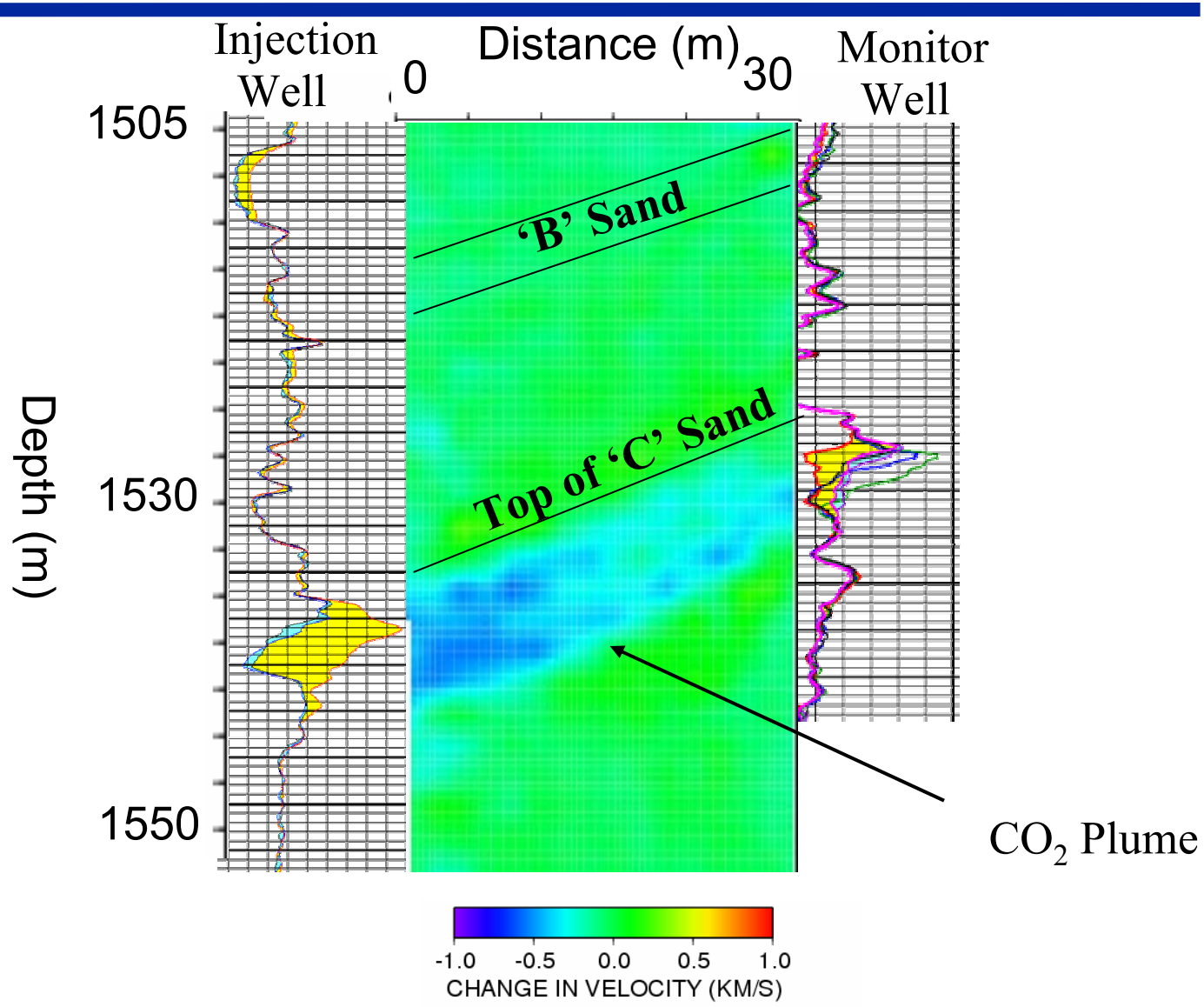
Crosswell Tomographic Inversion

- *Invert difference; not difference inversions*
- *2 m pixel size*
- Limit ray angle (no long offsets, > 100 m)
- Correct for deviation of wells
- Use straight ray projection
- Apply static correction (borehole effects)
- Plotting interpolated to 0.5 m
- Thanks to J.E. Peterson (LBNL), for inversion

Pre - Post Velocity Difference

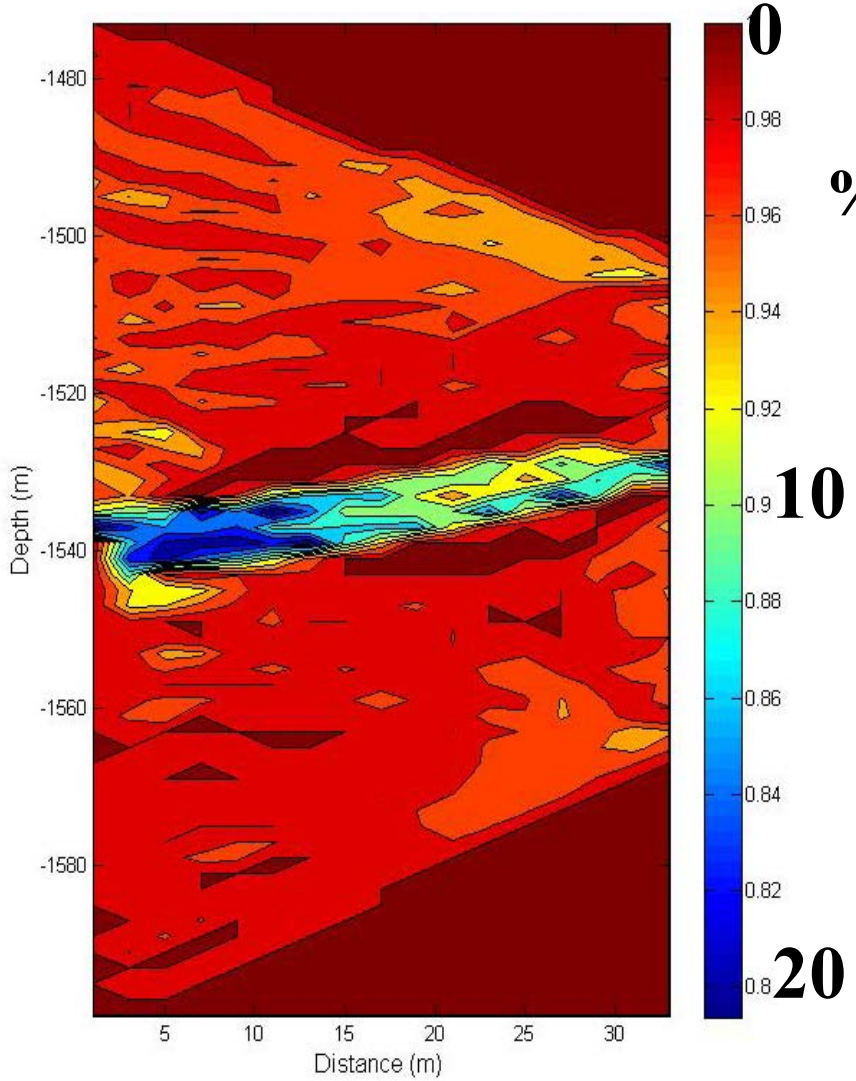


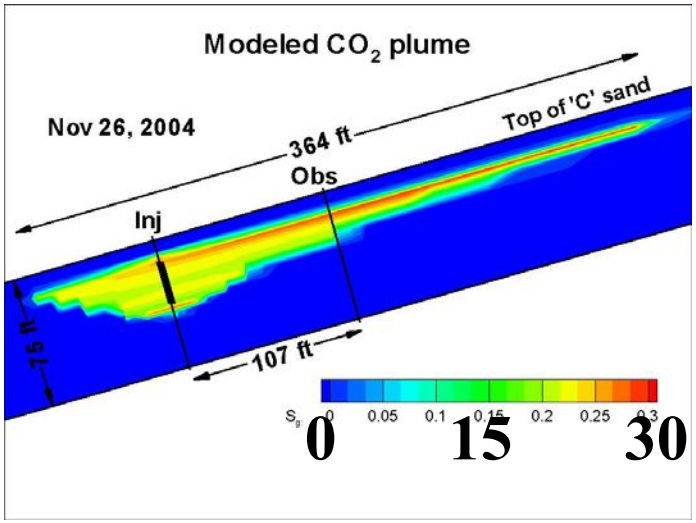
Seismic P-wave and Pulsed Neutron (RST) Logs



CO_2 Saturation From Seismic using a rock physics model

Crosswell Derived CO2 Saturation



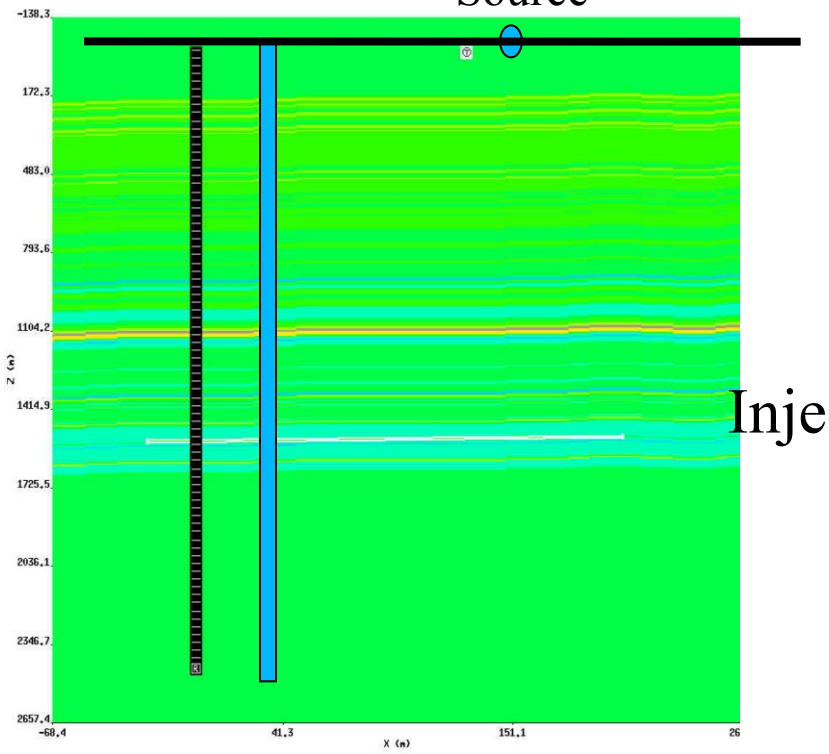


Result:
Crosswell seismic can be used to estimate CO_2 saturation spatially between wells.

Does the crosswell measurement explain the VSP result?

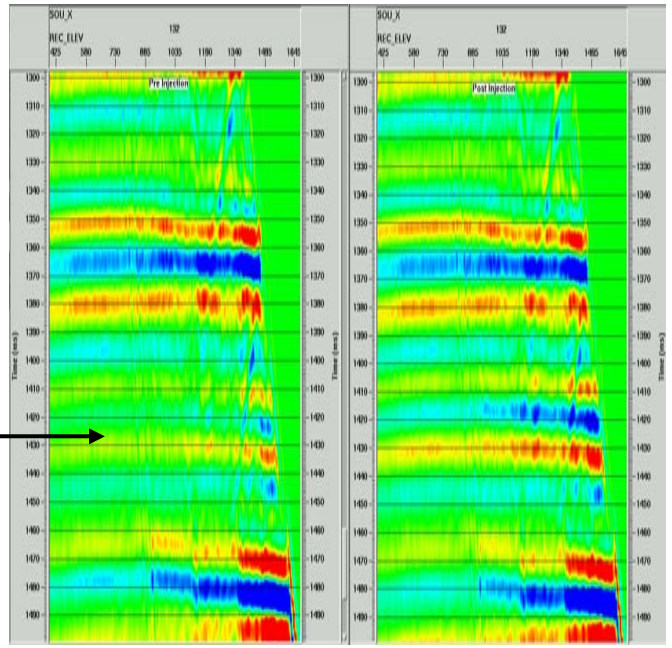
VSP Velocity Model

Source



Injection Zone

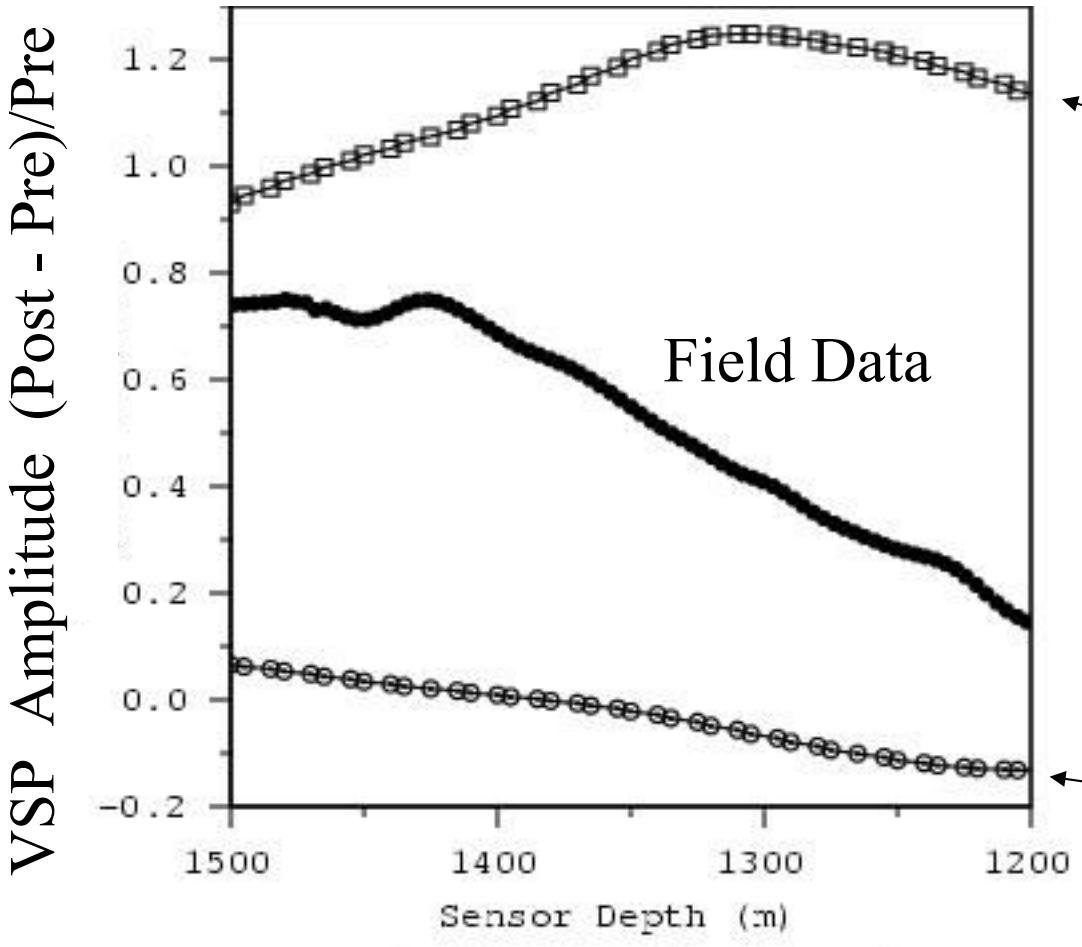
Modeled Data



Pre Post

Finite-Difference seismic modeling of VSP using Crosswell measured velocity shows changes observed in field.

Comparison of Model and Field VSP Data



Model with constant change for predicted plume extent > 130 m

Model with variable change, only between wells ~ 30 m

Result: Crosswell can predict VSP change if we know how to estimate CO_2 saturation beyond boreholes..

Conclusions

- Crosswell seismic images ~500 m/s (20%) velocity change due to CO_2 plume between wells. → Estimate CO_2 saturation with rock physics model
- VSP easily "sees" the plume as ~70% increase in reflection amplitude. → Some surface monitoring is possible without full 3D surface seismic.
- VSP can estimate the extent of CO_2 plume on different azimuths.
- Results of crosswell and VSP can be integrated with flow model to improve predictions of storage performance.

Concluding Comment and Plans for Frio-II

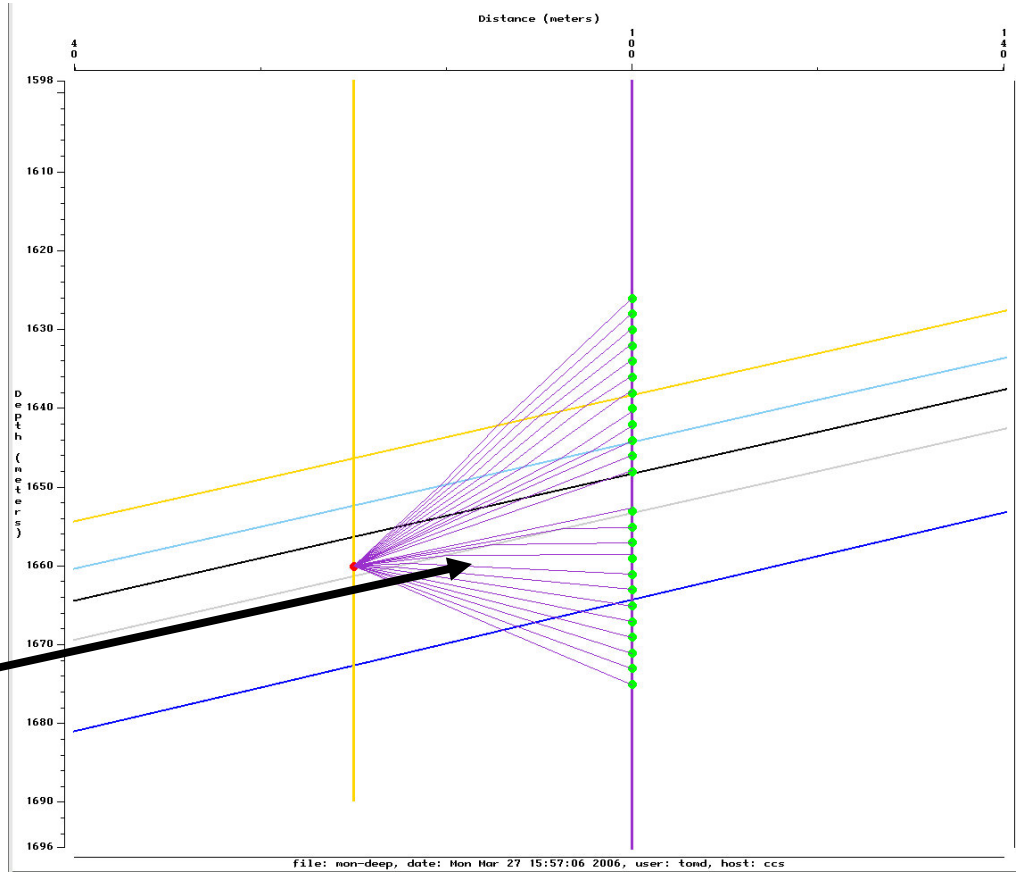
Permanent installation of seismic sensors could be a cost effective tool for characterization and long term monitoring of sequestered CO_2.

Frio – II Plans:

Semi-permanent, tubing-deployed crosswell monitoring during injection.

One source, 24 Sensors

Injection Interval:
'Blue' sand ~1650 m



Acknowledgements

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- Paulsson Geophysical (P/GSI) provided support for use of sensors
- Flow modeling by Chris Doughty (LBNL)

- Thank you for your attention!